

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
14 February 2002 (14.02.2002)

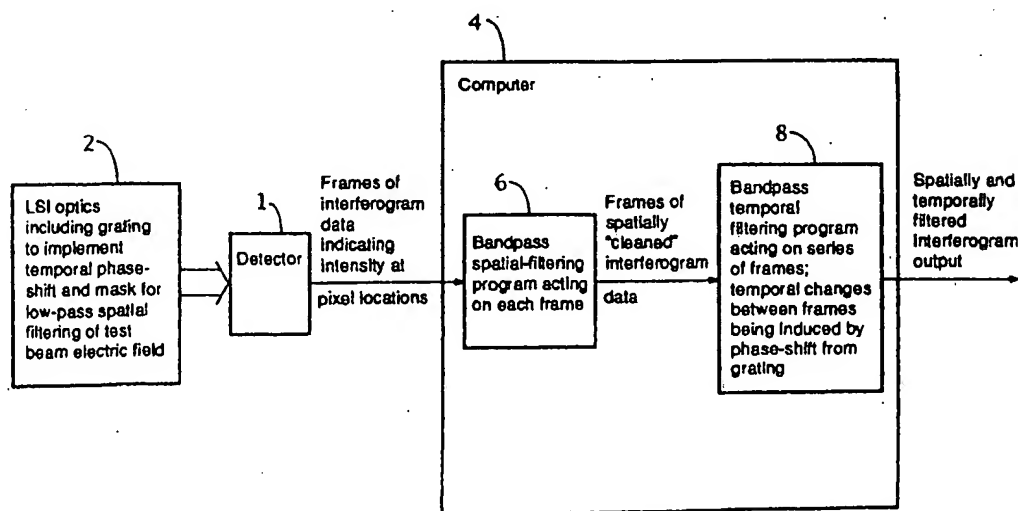
PCT

(10) International Publication Number
WO 02/12826 A1

- (51) International Patent Classification⁷: G01B 9/02, G01M 11/02, G03F 7/20
- (21) International Application Number: PCT/US01/41514
- (22) International Filing Date: 31 July 2001 (31.07.2001)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
09/632,631 4 August 2000 (04.08.2000) US
- (63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US 09/632,631 (CON)
Filed on 4 August 2000 (04.08.2000)
- (71) Applicant (for all designated States except US): **THE REGENTS OF THE UNIVERSITY OF CALIFORNIA** [US/US]; 1 Cyclotron Road, Bldg. 90-1121, Berkeley, CA 94720 (US).
- (72) Inventors; and
(75) Inventors/Applicants (for US only): **NAULLEAU, Patrick, P.** [US/US]; 5239 Miles Avenue, Apt. A, Oakland, CA 94618 (US). **GOLDBERG, Kenneth, Alan** [US/US]; 1195 Keeler Avenue, Berkeley, CA 94708 (US).
- (49) Agent: **JEW, Charles, H.; Burns, Doane, Swecker & Mathis, LLP**, P.O. Box 1404, Alexandria, VA 22314-1404 (US).
- (81) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.
- (84) Designated States (regional): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).
- Published:
— with international search report
— before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments

[Continued on next page]

(54) Title: **DUAL-DOMAIN LATERAL SHEARING INTERFEROMETER**



(57) Abstract: A defocused implementation of the lateral shearing interferometer in which an image-plane filter allows both phase-shifting and Fourier wavefront recovery methods to be readily used. The two wavefront recovery methods can be combined in a dual-domain technique providing suppression of noise added by self-interference of high-frequency components in the test-optic wavefront.



For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

DUAL-DOMAIN LATERAL SHEARING INTERFEROMETER

Field of the Invention

5 The present invention relates to lateral shearing interferometers (LSI) for making highly accurate measurements of wavefront aberrations. The invention overcomes the inaccuracies associated with conventional implementations of grating-based LSIs.

10 References

The following publications are cited in this application as superscript numbers:

1. G. E. Sommargren, "Diffraction methods raise interferometer accuracy," Laser Focus World, 32, 61-71, (8/96).

2. A. K. Ray-Chaudhuri, et al, "Alignment of a multilayer-coated imaging
15 system using extreme ultraviolet Foucault and Ronchi interferometric testing," J. Vac Sci Technol. B, 13, 3089-3093 (1995).

3. H. Medeck, et al, "Phase-shifting point diffraction interferometer," Opt. Lett., 21, 1526-1528 (1996).

20 4. P. Naulleau et al, "Characterization of the accuracy of EUV phase-shifting point diffraction interferometry," in *Emerging Lithographic Technologies II*, Yuli Vladimirovski, Editor, Proceedings of SPIE Vol. 3331, 114-123, (1998).

5. P. Carre, "Installation et utilisation du comparateur photoelectric et interferential du bureau international des poids et mesures," *Metrologia*, 2, 13-17 (1966).
- 5 6. R. Crane, "Interference phase measurement," *Appl. Opt.*, 8, 538-542 (1969).
7. J. H. Bruning, et al, "Digital wavefront measuring interferometer for testing optical surfaces and lenses," *Appl. Opt.*, 13, 2693-2703 (1974).
- 10 8. M. Takeda, et al, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," *J. Opt. Soc. Am.*, 72, 156-160 (1982).
- 15 9. E. Leith, et al, "Electronic holography and speckle methods for imaging through tissue using femtosecond gated pulses," *Appl. Opt.*, 30, 4204-4210 (1991).
10. K. A. Goldberg, et al, "A 3-D numerical study of pinhole diffraction to predict the accuracy of EUV point diffraction interferometry," *OSA Trends in Optics and Photonics Vol. 4, Extreme Ultraviolet Lithography*, G. D. Kubiak and D. R. Kania, eds, (Optical Society of America, Washington, DC 1996), pp. 133-137.
- 20 11. D. A. Tichenor, et al, "Development and characterization of a 10x Schwarzschild system for SXPL," in *OSA Proceedings on Soft X-Ray Projection Lithography*, Vol. 18, A. M. Hawryluk and R. H. Stulen, eds., (Optical Society of America, Washington, DC, 1993), pp. 79-82.
- 25 12. P. de Groot, "Derivation of algorithms for phase-shifting interferometry using the concept of a data-sampling window," *Appl. Opt.*, 34, 4723-4730 (1995).

13. K. Freischlad and C. Koliopoulos, "Fourier description of digital phase-measuring interferometry," *J. Opt. Soc. Am. A*, 7, 542-551 (1990).
- 5 14. Y. Surrel, "Design algorithms for phase measurements by the use of phase stepping," *Appl. Opt.*, 35, 51-60 (1996).
15. J. Tome and H. Stahl, "Phase-measuring interferometry: applications and techniques," in *Optical Testing and Metrology II*, Proceedings of SPIE Vol. 954, 71-77 (1988).
- 10 16. K. Creath, "Comparison of phase-measuring algorithms" in *Surface Characterization and Testing*, Proceedings of SPIE Vol. 680, 19-28 (1986).
- 15 17. H. Stahl, "Review of phase-measuring interferometry," in *Optical Testing and Metrology III: Recent Advances in Industrial Optical Inspection*, Proceedings of SPIE Vol. 1332, 71-77 (1990).
18. J. E. Bjorkholm, et al., "Phase-measuring interferometry using extreme ultraviolet radiation," *J. Vac. Sci. & Technol. B*, 13, 2919-2922 (1995).
- 20 19. P. Naulleau, et al., "The EUV phase-shifting point diffraction interferometer: a sub-angstrom reference-wave accuracy wave front metrology tool," *Appl. Opt.*, 38, 7252-7263 (1999).
20. K. A. Goldberg, "Extreme Ultraviolet Interferometry," Ph.D. dissertation (University of California, Berkeley, 1997).
21. D. Attwood, et al., "Tunable coherent radiation in the soft X-ray and

extreme ultraviolet spectral regions," IEEE J. Quantum Electron., 35, 709-720 (1999).

22. V. Ronchi, "Forty years of history of a grating interferometer," Appl. Opt., 3, 437-451 (1964).

23. A. Lohmann and O. Bryngdahl, "A lateral wavefront shearing
5 interferometer with variable shear," Appl. Opt., 6, 1934-1937 (1967).

24. S. Yokozeki and T. Suzuki, "Shearing interferometer using the grating
as the beam splitter," Appl. Opt., 10, 1575-1580 (1971).

25. J. C. Wyant, "Double frequency grating lateral shear interferometer,"
Appl. Opt., 12, 2057-2060 (1973).

10

26. H. O. Bartlett and Yajun Li, "Lau interferometry with cross gratings,"
Optics Comm., 48, 1-6 (1983).

27. J. C. Wyant, "Use of an ac heterodyne lateral shear interferometer with
real-time wavefront correction systems," Appl. Opt., 14, 2622-2626 (1975).

15 28. J. Schwider, "Single sideband Ronchi test," Appl. Opt., 20, 2635-2642
(1981).

29. J. Braat and A. Janssen, "Improved Ronchi test with extended source,"
J. Opt. Soc. Am. A, 16, 131-140 (1999).

20 30. P. Naulleau and K. A. Goldberg, "Dual-domain point diffraction
interferometer," Appl. Opt., 38, 3523-3533 (1999).

31. D. Malacara, *Optical Shop Testing*, (John Wiley & Sons, New York, 1992), pp. 346-348.

32. D. W. Sweeney, et al., "EUV optical design for a 100 nm CD imaging system," in *Emerging Lithographic Technologies II*, Y. Vladimirsky, ed., Proc. SPIE
5 Vol. 3331, 2-10 (1998).

33. M. P. Rimmer, "Method for evaluating lateral shearing interferograms," *Appl. Opt.*, 13, 623-629 (1974).

10 All of the above publications are herein incorporated by reference in their entirety to the same extent as if each individual publication was specifically and individually indicated to be incorporated by reference in its entirety.

Background of the Invention

15 The recent development of extreme ultraviolet (EUV) optics for use in next-generation lithography systems has led to several advancements in EUV interferometry.^{2,3,18} With a demonstrated reference-wavefront accuracy of better than $\lambda_{\text{EUV}}/350$ (0.04 nm at $\lambda_{\text{EUV}} = 13.4$ nm)¹⁹, the phase-shifting point diffraction interferometer (PS/PDI)^{3,19,20} is believed to be the most accurate EUV interferometer available. Although the PS/PDI has been proven to have high-accuracy, broad
20 applicability of the PS/PDI is severely limited by its small dynamic range and the fact that it must be used with a highly coherent EUV source such as undulator radiation.²¹

An alternative to the PS/PDI, with relaxed coherence requirements, is the lateral shearing interferometer (LSI).²²⁻²⁹ The Ronchi interferometer²² is perhaps the simplest realization of the LSI. Although not yet fully characterized for accuracy at EUV, this
25 type of interferometer has previously been used for at-wavelength characterization of EUV optics.^{2,18} More recently, a carrier-frequency (off-axis) implementation of the Ronchi interferometer has been used in the characterization of an EUV Schwarzschild

objective. Direct comparison of this carrier-frequency LSI to the PS/PDI has demonstrated a rms measurement agreement of $\sim \lambda_{\text{EUV}}/70$. However, the development of next-generation EUV lithography systems requires interferometry with accuracy preferably far exceeding $\lambda_{\text{EUV}}/100$.

5 A problem with the conventional Ronchi interferometer is that it produces many interfering beams causing confusion in the data analysis and limiting the accuracy of the device. Another problem with this simple interferometer, limiting its accuracy, is that it is susceptible to noise added by high-frequency components in the test-optic wavefront.

10 Various methods have been described to overcome the limitation caused by multiple interfering beams. One particularly simple and elegant solution is the single-sideband LSI.²⁸ In operation of the single-sideband LSI, an illumination beam is spatially filtered by a pinhole in the object plane, thus illuminating the test optic with a nearly spherical wave. A grating beamsplitter is placed in front of the image plane,
15 where the illuminating beam is focused. Two of the diffracted orders propagate through a single large window in an image-plane mask with the remainder of the diffracted orders being blocked by the mask. Typically the two orders are chosen to be the zero order and either the +1 or the -1 order. The two beams propagate to the detector where they overlap. While the zeroth-order beam propagates to the detector in the same
20 manner as it would if the grating were not present, the diffracted order propagates with an angular shear, leading to a (typically) small lateral displacement at the detector. In this way, the test beam is compared with a sheared (laterally displaced) copy of itself.

 The image-plane window serves several roles. One role is to guarantee that only two grating orders reach the detector, thus the Talbot effect of fringe localization³¹
25 becomes irrelevant. Without these windows the position of the grating would be limited to a discrete set of defocus planes. Another effect of having only two interfering grating orders is that the recorded fringe pattern will be sinusoidal instead of square, facilitating the fringe analysis. Finally, confusion of multiple beam interference is avoided because only two beams are allowed to interfere at the detector.

In this simple two-beam interference case, analysis of the resultant interferogram reveals an approximation to the gradient of the test wavefront, or the derivative in the direction of the shear. The original wavefront can be recovered by combining gradients from two (or more) directions using a variety of well-known techniques such as the Rimmer method.³³ Although the single-sideband LSI solves the multiple-beam interference problem it does not address the issue of noise susceptibility due to high-frequency features in the test-optic wavefront.

An alternative solution to the multiple-beam interference problem is to use double-frequency gratings where only the first-diffracted orders of the two constituent gratings overlap.²⁵ This method, however, is not well suited to EUV interferometry due to the difficulty in fabricating the dual-high-frequency gratings. Achieving full order separation when testing an EUV optic ($\lambda = 13.4$ nm) with a moderate numerical aperture (NA) of 0.1 would require a grating pitch of 67 nm with accuracy to a small fraction of that pitch. Also it does not address the issue of noise susceptibility due to high-frequency features in the test-optic wavefront.

A third solution to the multiple-beam interference problem is ac heterodyning (phase shifting).^{27,18} In this case, the grating is translated laterally, orthogonal to the grating lines, producing temporal modulation of the intensity at each pixel at the detector. Temporal filtering is used to eliminate higher-order interference terms. Achieving high accuracy with this method when square-wave gratings are used, and hence square-wave temporal modulation is produced, requires a large number of samples to be recorded with very accurate grating translation. Because EUV systems are typically limited to using square-wave (binary) gratings due to fabrication issues, this method does not provide a time-efficient solution. Again this method does not address the issue of noise susceptibility due to high-frequency features in the test-optic wavefront.

Summary of the Invention

The present invention relates to a defocused implementation of the LSI in which

an image-plane filter is employed to allow both phase-shifting and Fourier wavefront recovery methods to be used. Furthermore, the two wavefront recovery methods can be combined in a dual-domain technique providing suppression of noise added by self-interference of high-frequency components in the test-optic wavefront.

5 In one embodiment, the invention is directed to a method of generating an interference pattern with a lateral shearing interferometer that includes the steps of:

(a) directing a source of radiation toward a test optic provided in a test-optic region of the lateral shearing interferometer whereby the test optic focuses a beam of radiation to an image plane located downstream from the test optic;

10 (b) dividing the beam of radiation into a first output beam and a second output beam directed at different angles with respect to one another such that the first output beam impinges at a first location on the image plane and the second output beam impinges at a second location, that is laterally separated from the first location, on the image plane; wherein the first and second locations on the image plane onto which the
15 first and second output beams impinge define a beam-separation angle;

(c) phase shifting at least one of the first output beam and the second output beam;

(d) passing the first output beam through a first window on a mask that is positioned at the image plane of the test optic to produce a first wave and passing the
20 second output beam through a second window on the mask to produce a second wave;

(e) recording a set of interference patterns (interferograms), with relative phase shifting between each element of the set;

(f) recovering a first shearing wavefront by processing the recorded interferograms in both temporal and spatial domains;

25 (g) repeating steps (b) through (f) at at least one different beam-separation angle to recover at least one other shearing wavefront; and

(h) combining the shearing wavefronts to recover a test-optic wavefront.

In another embodiment, the invention is directed to a lateral shearing interferometer system that defines an optical path, said system including:

-9-

- (a) an optical system under test;
- (b) a source of electromagnetic energy that directs a beam of radiation toward the optical system which focuses the beam of radiation;
- (c) a beam divider in the optical path for dividing the beam of radiation from
5 the optical system into a first beam and a second beam;
- (d) a mask that is positioned in the image plane of the optical system under test wherein the first beam passes through a first window on the mask and the second beam through a second window on the mask, wherein the first beam and second beam are directed at different angles with respect to one another such that the first beam
10 impinges at a first location on the image plane and the second beam impinges at a second location, laterally separated from the first location, on the image plane, wherein the first and second locations on the image plane onto which the first and second beams impinge define a beam-separation angle;
- (e) a phase-shifting mechanism for adjusting the phase of at least one of the first
15 beam or second beam;
- (f) a detector located downstream from the mask for recording a set of interference patterns (interferograms), with relative phase shifts between each element of the set;
- (g) means for recovering the shearing wavefront by process the recorded
20 interferograms in both temporal and spatial domains; and
- (h) means for combing two or more shearing wavefronts that are measured at different beam-separation angles to recover a test-optic wavefront.

Brief Description of the Drawings

25 Fig. 1 illustrates the dual-domain implementation of the lateral shearing interferometer (LSI) with image-side grating;

Fig. 2(a) depict the limits of the detector-plane-field spectral content in one dimensions as set by the image-plane spatial filter and (b) the spatial-spectrum limits of the recorded interferogram; and

Fig. 3 is a diagram illustrating operation of one embodiment of the dual-domain LSI.

Detailed Description of the Preferred Embodiments

In the dual-domain implementation of the LSI as illustrated in Fig. 1, the optic under test is preferably illuminated by a nearly spherical wave emanating from the object plane of the optic under test. A shearing grating is placed on the image side of the optic under test in a plane in front of the image plane. As opposed to the single-sideband method described above, the dual-domain method uses a pair of windows in the image plane aligned to selectively pass two orders of the grating.

The pair of windows in the dual-domain case serve all the same roles described for the single window in the single-sideband case: 1) eliminates the Talbot fringe localization effect,³¹ 2) produces a sinusoidal fringe pattern, 3) eliminates the multiple-beam interference problem. In addition to these benefits, the dual-domain windows also act as spatial filters that prevent self-interference and aliasing corruption of the desired signal.

The desired signal is the interference between two separate orders of the grating. If the image-plane windows are too large, or a single window is used (as is the case in the single-sideband method), the spatial-frequency content of the desired signal is likely to overlap with the spatial-frequency content of the self-interference term of each individual beam. By combining the use of these windows with both phase-shifting⁵⁻⁷ and Fourier-fringe analysis⁸ methods this self-interference effect can be eliminated.

Another advantage of using two separate windows is that the potential aliasing problem is avoided. Aliasing occurs when the shear is larger than the smallest features of the two individual wavefronts. In this case, the shearing wavefront no longer represents the derivative of the test-optic wavefront because the signal is effectively undersampled. The two individual windows can be viewed as antialiasing filters allowing the sampling criterion to be met by limiting how small

features can be in the two copies of the test-optic wavefront that actually interfere at the detector.

To eliminate the self-interference corruption, the window center-to-center separation for the image-plane mask should be set to at least twice the window width. Furthermore, the window width should be chosen to be compatible with the spatial-frequency content expected from the optic under test. The grating position and pitch should be chosen to provide an image-plane beam separation equal to the window center-to-center separation. Finally, the grating pitch should also be selected to provide the desired detector-plane shear Δ avoiding aliasing.

In one embodiment, the LSI includes a source of radiation that precedes an object pinhole spatial-filter containing a pinhole. Moreover, the grating beam splitter (e.g, transmission grating) is placed following the test optic in a plane preceding the image plane. In the image plane is placed a two-window mask. Typically, an irradiance detector is used to record the interference patterns.

Examples of irradiance detectors include a camera with a photosensitive film, and a Vidicon camera; a preferred detector is a charged-couple device (CCD). Particular features of the LSI, excluding the dual-domain features, are further described by Goldberg and Naulleau in U.S. Patent Application entitled "Hybrid Shearing and Phase-shifting Point Diffraction Interferometer" serial no. 09/617,719, filed July 17, 2000 which is incorporated herein.

Dual-Domain Implementation for LSI

In the past, LSI data analysis had primarily been performed using either time-domain (phase-shifting) methods,^{5-7, 18, 27} or spatial-domain methods such as the Fourier-transform method.^{8, 28} The dual-domain LSI of the present invention, however, is well suited to using both methods and as described above, distinct advantages are obtained when the two methods are simultaneously combined.

In practice, it is difficult to strictly meet the bandwidth criterion that would prevent the self-interference corruption and aliasing problems described above.

Limiting the self-interference corruption problem in the conventional single-sideband case, requires the interferogram carrier frequency to be significantly larger than the bandwidth of the test-optic wavefront. Failure to meet this criterion causes light from adjacent orders in the recorded interferogram to spill into the signal band of interest corrupting the measurement. A problem very similar to this has recently
5 been addressed in the PS/PDI³ through the development of a dual-domain data collection and analysis technique.³⁰ This same dual-domain technique, with slight modifications of the image-plane mask, can also be applied to the LSI problem.

Derivation of the dual-domain process is described in detail by Naulleau and
10 Goldberg in U.S. Patent Application serial no. 09/300,539 entitled "Dual-Domain Point Diffraction Interferometer" filed April 27, 1999 and in "Dual-domain point diffraction interferometer," Appl. Opt, 38, 3523-3533 (1999), which are both incorporated herein by reference. The method relies on collecting a temporally modulated (phase-shifting) series of carrier-frequency interferograms. The method
15 is essentially a three-tiered filtering system composed of lowpass spatial-filtering the test-beam electric field, bandpass spatial-filtering the individual interferogram irradiance frames of a phase-shifting series, and bandpass temporal-filtering the phase-shifting series as a whole. The first step is physical and is achieved by way of focal-plane windows; whereas the last two steps are implemented numerically. The
20 dual-domain LSI can be viewed as a combination of the ac-heterodyne and single-sideband LSIs described above. As with the original single-sideband method, the dual-domain technique eliminates ambiguities caused by multi-beam (more than two) interference.

The dual-domain method is best described in the Fourier domain. It is
25 assumed that the detector is in the far field of the focal plane, thus, spatial frequencies at the detector are equivalent to lateral displacements in the focal plane: $f_x \approx x/(\lambda z)$, where f_x is spatial frequency in the detector plane, x is lateral displacement in the focal plane, z is the distance between the focal and detector planes, and λ is the illumination wavelength. In the dual-domain method, a spatial

-13-

filter comprised of two windows respectively centered on two diffracted orders of the grating is placed in the focal plane. The window widths are chosen small enough to prevent spatial-frequency cross-talk between adjacent orders in the recorded interferogram. This differs from the single-sideband method, which typically uses a single image-plane window to pass both orders. Typically, the first window has an area of between $1 \mu\text{m}^2$ and 0.01 mm^2 and the second window has an area of between $1 \mu\text{m}^2$ and 0.01 mm^2 and the separation between the center of the first window and the center of the second window is between $2 \mu\text{m}^2$ and 0.2 mm^2 .

Noting that the recorded interferogram is simply the modulus squared of the Fourier transform of the focal-plane field distribution, the Autocorrelation Theorem can be used to find the spatial-spectrum limits of the recorded interferogram. Fig. 2(a) depicts the limits of the detector-plane-field spectral content in one dimension as set by the image-plane spatial filter (windows) and Fig. 2(b) shows the autocorrelation of the field spectrum or the recorded intensity spectrum. The central peak is the *zero-order* interferogram term: this is essentially the irradiance of the light passing through the windows. The two off-axis components are the positive- and negative-first-order interferogram terms that arise from the interference between the sheared beams. To prevent overlap between adjacent orders, the window separation, and hence focal-plane beam separation is most preferably at least twice the window width. This separation differs from the PS/PDI dual-domain case where the beam separation is only required to be $3/2$ the window width.³⁰ The difference comes from the fact that in the PS/PDI the reference-beam spectrum is essentially a delta function, whereas in the LSI, the reference is a copy of the test beam.

The condition described above guarantees that the self-interference term of the light traveling through each individual window will not corrupt the signal of interest comprised of the interference between two different orders of the grating, each propagating through a separate window. It should be noted, however, that light from a single order of the grating traveling through both windows and interfering at

the detector will not be separable from the signal of interest in the spatial-frequency domain. Using the two-window mask with simple Fourier-fringe analysis would, hence, be incapable of completely eliminating the high-frequency corruption. This single-beam cross-window term, however, will not phase shift as it arises from a single order of the grating. Phase shifting requires two different orders of the grating to interfere. The fact that this term does not phase shift while the signal of interest does, means that it can be eliminated by temporal-domain (phase-shifting) analysis. By combining the two analysis methods as is done in the dual-domain method, both major self-interference corruption terms are eliminated.

The dual-domain analysis method can be implemented in various ways. One way is to record a set of phase-shifting interferograms and to numerically spatially filter each interferogram using a Fourier-domain filter chosen to match the location and size of the first-diffracted order of each interferogram. This set of filtered interferograms is then processed using conventional phase-shifting (time-domain) methods.⁵⁻⁷ The resulting wavefront is a shearing wavefront (derivative in the direction of the shear). To recover the test-optic wavefront, this process is repeated at at least one different shear direction and the shearing wavefronts combined using conventional shearing analysis methods such as the Rimmer method.³³

Alternatively, the temporal domain (phase-shifting analysis) process can be implemented first to recover a still-partially-corrupted complex-valued shearing wavefront and the spatial filtering subsequently performed as described above to remove the residual corruption. Finally, the spatial filtering process may also be directly embedded into the phase-shifting analysis.

Fig. 3 is a diagram that illustrates the operation of one embodiment of the dual-domain LSI data collection and processing system. A detector 1 detects an interferogram produced by the optic under test 2. The interferogram changes over time as a result of the phase-shifting caused by lateral translation of the grating. The detector 1 produces an output that is sent to a computer 4. The output consists of a number of frames (at least 3) of data produced at different times. Each frame has an

-15-

intensity value for each pixel of the detector.

A spatial-filtering program 6 residing in the computer 4 spatially filters each recorded frame separately as described above. The spatial-filtering program 6 produces frames of spatially "cleaned" data; the noise term arising from self-interference of light propagating through each individual window has been eliminated.

A program implementing a phase-shifting-interferometry algorithm (temporal-domain processing) 8 uses the series of "cleaned" frames to produce the wavefront output. This step simultaneously acts as a temporal filtering step, removing the self-interference noise arising from the light from a single grating order propagating through both windows.

Although only preferred embodiments of the invention are specifically disclosed and described above, it will be appreciated that many modifications and variations of the present invention are possible in light of the above teachings and within the purview of the appended claims without departing from the spirit and intended scope of the invention.

-16-

What is Claimed is:

1. A method of generating an interference pattern with a lateral shearing interferometer that comprises the steps of:

(a) directing a source of radiation toward a test optic provided in a test-optic region of the lateral shearing interferometer whereby the test optic focuses a beam of radiation to an image plane located downstream from the test optic;

(b) dividing the beam of radiation into a first output beam and a second output beam directed at different angles with respect to one another such that the first output beam impinges at a first location on the image plane and the second output beam impinges at a second location, that is laterally separated from the first location, on the image plane, wherein the first and second locations on the image plane onto which the first and second output beams impinge define a beam-separation angle;

(c) phase shifting at least one of the first output beam and the second output beam;

(d) passing the first output beam through a first window on a mask that is positioned at the image plane of the test optic to produce a first wave and passing the second output beam through a second window on the mask to produce a second wave;

(e) recording a set of interference patterns (interferograms), with relative phase shifting between each element of the set;

(f) recovering a first shearing wavefront by processing the recorded interferograms in both temporal and spatial domains;

(g) repeating steps (b) through (f) at at least one different beam-separation angle to recover at least one other shearing wavefront ; and

(h) combining the shearing wavefronts to recover a test-optic wavefront.

2. The method of claim 1 wherein the sizes of the first window and second

-17-

window are sufficiently small to prevent spatial-frequency cross-talk between adjacent orders in the recorded interferogram.

3. The method of claim 1 or 2 wherein the separation between the center of the first window and the center of the second window is at least two times the window width.
4. The method of any preceding claim wherein the first window has an area of between $1 \mu\text{m}^2$ and 0.01 mm^2 and the second window has an area of between $1 \mu\text{m}^2$ and 0.01 mm^2 and the separation between the center of the first window and the center of the second window is between $2 \mu\text{m}^2$ and 0.2 mm^2 .
5. The method of any preceding claim wherein the size and shape of the first window is essentially identical to that of the second window.
6. The method of any preceding claim wherein the beam divider is a diffraction grating.
7. The method of any preceding claim wherein the recording device is a charged-coupled device.
8. The method of any of claims 1-7 wherein step (f) comprises (i) bandpass spatial-filtering the individual phase-shifting interferogram's irradiance frames to form a filtered phase-shifting series, and (ii) using time-domain-based techniques to recover the shearing wavefront from the resulting filtered phase-shifting series.
9. The method of any of claims 1-7 wherein step (f) comprises (i) using time-domain-based techniques to recover the complex amplitude of the shearing wavefront from the phase-shifting series as a whole, and (ii) bandpass spatial-

-18-

filtering the resulting complex amplitude to eliminate the spatial-frequency crosstalk from the shearing wavefront.

10. The method of claim 8 wherein the bandpass filter, as defined in the spatial-frequency domain, is (i) essentially equal to twice the test-beam window size as
5 defined in the spatial-frequency domain and (ii) is centered on the positive- and/or negative-first orders of the recorded interferograms.

11. The method of claim 9 wherein the bandpass filter, as defined in the spatial-frequency domain, is (i) essentially equal to twice the test-beam window size, as
10 defined in the spatial-frequency domain, and (ii) centered on the Fourier-domain peak of the complex amplitude.

12. The method of any of claims 1-7 wherein step (f) comprises embedding a bandpass spatial-filtering process into a time-domain technique algorithm, thereby, simultaneously processing the data in both the temporal and spatial domains.

13. A lateral shearing interferometer system that defines an optical path, said
15 system comprising:

- (a) an optical system under test;
- (b) a source of electromagnetic energy that directs a beam of radiation toward the optical system which focuses the beam of radiation;
- (c) a beam divider in the optical path for dividing the beam of radiation from
20 the optical system into a first beam and a second beam;
- (d) a mask that is positioned in the image plane of an optical system under test wherein the first beam passes through a first window on the mask and the second beam through a second window on the mask, wherein the first beam and second beam are directed at different angles with respect to one another such that
25 the first beam impinges at a first location on the image plane and the second beam

-19-

impinges at a second location, laterally separated from the first location, on an image plane, wherein the first and second locations on the image plane onto which the first and second beams impinge define a beam separation angle;

5 (e) a phase shifting mechanism for adjusting the phase of at least one of the first beam or second beam;

(f) a detector located downstream from the mask for recording a set of interference patterns (interferograms), with relative phase shifts between each element of the set;

10 (g) means for recovering shearing wavefront by processing the recorded interferograms in both temporal and spatial domains; and

(h) means for combing two or more shearing wavefronts that are measured at different beam separation angles to recover a test-optic wavefront.

14. The system of claim 13 wherein the sizes of the first window and second window are sufficiently small to prevent spatial-frequency cross-talk between
15 adjacent orders in the recorded interferogram.

15. The system of claim 13 or 14 wherein the separation between the center of the first window and the center of the second window is at least two times the window width.

20 16. The system of any of claims 13-15 wherein the first window has an area of between $1 \mu\text{m}^2$ and 0.01 mm^2 and the second window has an area of between $1 \mu\text{m}^2$ and 0.01 mm^2 and the separation between the center of the first window and the center of the second window is between $2 \mu\text{m}^2$ and 0.2 mm^2 .

17. The system of any of claims 13-16 wherein the size and shape of the first window is essentially identical to that of the second window.

25 18. The system of any of claims 13-17 wherein the beam divider is a diffraction

-20-

grating.

19. The system of any of claims 13-18 wherein the recording device is a charged-coupled device.

20. The system of any of claims 13-19 wherein the means for recovering the shearing wavefront comprises means for (i) bandpass spatial-filtering the individual interferogram's irradiance frames to form a filtered phase-shifting series, and (ii) using time-domain-based techniques to recover the shearing wavefront from the resulting filtered phase-shifting series.

21. The system of any of claims 13-19 wherein the means for recovering the shearing wavefront comprises means for (i) using time-domain-based techniques to recover the complex amplitude of the shearing wavefront from the phase-shifting series as a whole, and (ii) bandpass spatial-filtering the resulting complex amplitude to eliminate the spatial-frequency crosstalk from the shearing wavefront.

22. The system of claim 20 wherein the means for bandpass spatial-filtering, as defined in the spatial-frequency domain, is (i) essentially equal to twice the test-beam window size as defined in the spatial-frequency domain and (ii) is centered on the positive- and/or negative-first orders of the recorded interferograms.

23. The system of claim 21 wherein the bandpass spatial-filtering means, as defined in the spatial-frequency domain, is (i) essentially equal to twice the test-beam window size, as defined in the spatial-frequency domain, and (ii) centered on the Fourier-domain peak of the complex amplitude.

24. The system of any of claims 13-19 wherein the means for recovering the shearing wavefront comprises a bandpass spatial-filtering process that is embedded

-21-

into a time-domain technique algorithm, thereby, simultaneously processing the data in both the temporal and spatial domains.

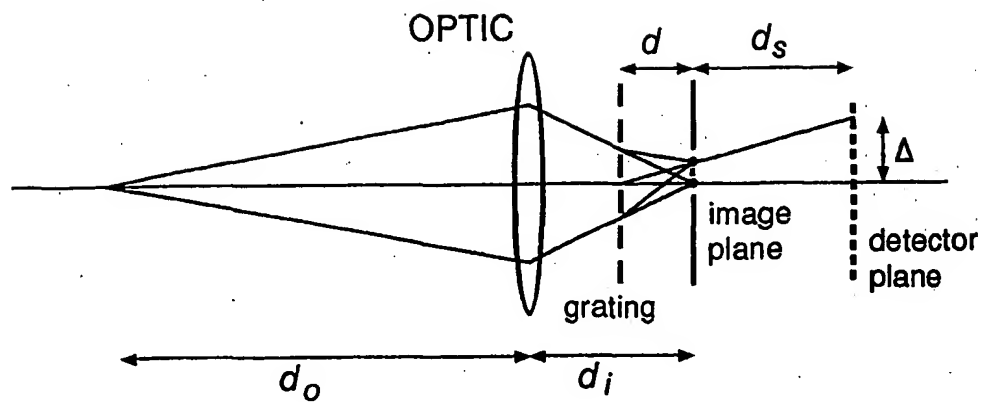


FIG._1.

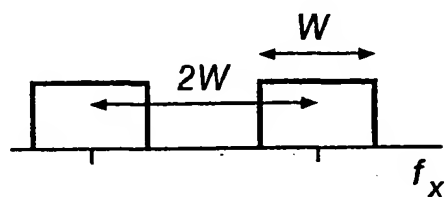


FIG._2A.

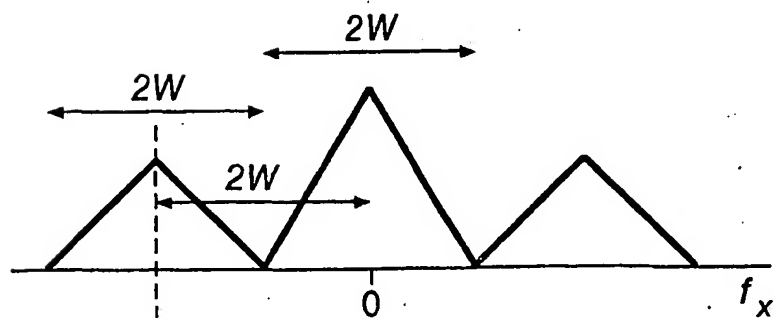


FIG._2B.

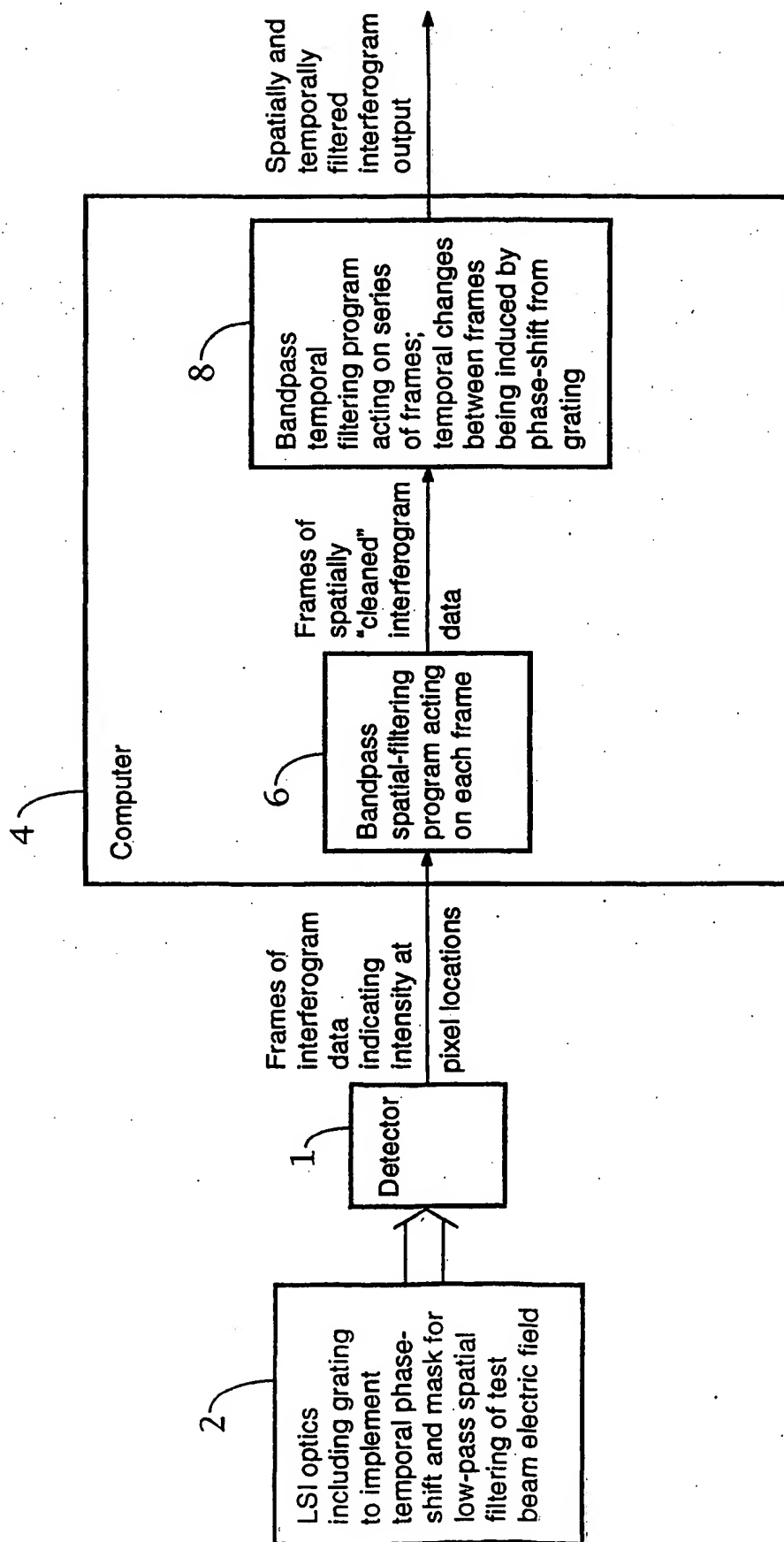


FIG._3.

INTERNATIONAL SEARCH REPORT

International Application No.

PCT/US 01/41514

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G01B9/02 G01M11/02 G03F7/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G01B G01M G03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KIM S-W ET AL: "LATERAL-SHEARING INTERFEROMETER USING SQUARE PRISMS FOR OPTICAL TESTING OF ASPHERIC LENSES" MEASUREMENT SCIENCE AND TECHNOLOGY, IOP PUBLISHING, BRISTOL, GB, vol. 9, no. 7, July 1998 (1998-07), pages 1129-1136, XP000849197 ISSN: 0957-0233 abstract; figures 1,2	1,13
A	WO 92 20991 A (BLUE SKY RES INC) 26 November 1992 (1992-11-26) abstract; figures 1,3	1,2

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

& document member of the same patent family

Date of the actual completion of the international search

23 November 2001

Date of mailing of the international search report

03/12/2001

Name and mailing address of the ISA

European Patent Office, P.B. 5018 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Vorropoulos, G

INTERNATIONAL SEARCH REPORT
Information on patent family members

International Application No
PCT/US 01/41514

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
WO 9220991	A	26-11-1992	EP 0539571 A1	05-05-1993
			JP 6500405 T	13-01-1994
			WO 9220991 A1	26-11-1992

**This Page is Inserted by IFW Indexing and Scanning
Operations and is not part of the Official Record**

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

☐ BLACK BORDERS

☐ IMAGE CUT OFF AT TOP, BOTTOM OR SIDES

☒ FADED TEXT OR DRAWING

☒ BLURRED OR ILLEGIBLE TEXT OR DRAWING

☐ SKEWED/SLANTED IMAGES

☐ COLOR OR BLACK AND WHITE PHOTOGRAPHS

☐ GRAY SCALE DOCUMENTS

☐ LINES OR MARKS ON ORIGINAL DOCUMENT

☐ REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY

☐ OTHER: _____

IMAGES ARE BEST AVAILABLE COPY.

As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.